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QED-QCD Interference Effect on the Charge Dependent N-N Interaction

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Abstract

The charge symmetry breaking and charge independence breaking N-N $^1S_0$ scattering length differences, Δa_{CSB} and Δa_{CIB}, are calculated by a resonating group method with a quark cluster model. By adding the QED-QCD interference effect to the quark mass difference and the electromagnetic interaction, the Δa_{CSB} and Δa_{CIB} values can be reproduced with model parameters constrained by the hadron isomultiplet mass splitting.

There are two main approaches to hadronic interactions: One is the meson exchange model, the other, the quark cluster model. The meson exchange model[1] fits the hadron interactions quantitatively with the aid of many phenomenological meson-baryon coupling constants and form factors (or short range phenomenologies). Quark cluster models[2] bring a deeper understanding of the short range repulsion but most of them can not produce the N-N intermediate range attraction and must invoke effective meson exchange again. Wang *et al.*[3] have developed a model which takes into account quark delocalization and color screening, and so is able to reproduce the N-N short range repulsion and the intermediate range attraction simultaneously. It also draws an analogy between nuclear and molecular forces.

For the charge dependent N-N interaction, the meson exchange model attributes the charge independence breaking mainly to the π mass difference and the charge symmetry breaking mainly to $\rho - \omega$ mixing[4]. While accepting that the primary origins of the charge dependence of the hadronic interaction are the quark mass difference and the electromagnetic interaction, meson exchange model practitioners believe that these two effects play their role indirectly: The electromagnetic interaction affects the π masses and the quark mass difference induces the $\rho - \omega$ mixing. However, as pointed out by S.N. Yang and Pauchy W.-Y. Hwang[5], such an optimistic picture for the meson exchange model fit of the Δa_{CSB} and Δa_{CIB} is questionable. Different calculations of the $\pi^{\pm} - \pi^0$ mass difference effect on Δa_{CIB} give quite different results ranging from $2.64 \pm 0.16\ fm$ [6], through $3.11 \pm 0.1\ fm$[7] to $3.6 \pm 0.15\ fm$[8]. The $\gamma\pi$ contribution estimates are even more diverse, ranging from $-0.53\ fm$[9] to $0.67\ fm$[10] and a value of 1.1 fm is listed in table 3.3 of reference[4]. This is an average of two calculations with even more significantly different $\Delta a_{CIB}\,(\gamma\pi)$ values. Moreover, it has been argued that the $\rho - \omega$ mixing is strongly momentum transfer dependent and therefore the charge symmetry breaking in $N - N$ scattering due to $\rho - \omega$ mixing is strongly suppressed[11].

There are also direct quark model approaches to the charge dependent N-N interaction[12, 13], wherein the quark mass difference effect and the electromagnetic interaction have been taken into account. It seems generically impossible to fit the charge symmetry and charge independence breaking simultaneously in this kind of approach, because the quark mass difference does not affect the *n-p* scattering and the electromagnetic effect is not large enough[12] to reproduce the charge independence breaking. A related concern is that the quark mass difference is not directly observable, because the quarks are permanently confined. They are principally determined using hadron isomultiplet masses. A quark mass difference so determined is in turn dependent on the assumption of the primary origin of the charge dependence. Goldman, Maltman and Stephenson (GMS)[14] proposed that "QED-QCD interference" induces a charge dependent q-q interaction effect not taken into account in previous considerations. If this effect is included in the hadron isomultiplet mass fitting, GMS can fit the existing hadron isomultiplet masses (with large experimental errors) with a quark mass difference -4.96 MeV $\leq \Delta m (= m_d - m_u) \leq 6.28$ MeV. Their most favorable parameter set has Δm=0.66 MeV, which is quite different from the $\Delta m \sim 3$MeV recommended in Ref. [4] and the value used is quark model calculations[12, 13]. If the QED-QCD interference effect is really as important as proposed by GMS, this interference effect should be added to the quark mass difference and electromagnetic interaction and the charge symmetry breaking in nuclear and particle physics reanalyzed. The QED-QCD interference effect contributes to both charge symmetry and charge independence breaking. Our interest here is to check whether

one can produce the charge symmetry and charge independence breaking appearing in the N-N interaction simultaneously in a quark model approach by taking the quark mass difference, the electromagnetic interaction and the QED-QCD interference into account together.

It has been proven that for a color singlet system without explicit gluon excitations, the quark degree of freedom description and the colorless meson baryon degree of freedom descriptions are equivalent[15]. For a real calculation, however, the Hilbert space is always truncated. One then faces the question of which truncation–quark approach or meson baryon approach–is more efficient. Similarly, it is also worth considering which one–quark or meson baryon approach–is more efficient for the description of the charge dependent N-N interaction. It is well known that $\rho-\omega$ meson exchange is responsible for both the short range repulsion and the spin-orbit force of the N-N interaction. On the other hand, it has been shown that the N-N short range repulsion[2] and the spin-orbit splitting[16] can be deduced in the quark model approach. Therefore one expects that it should be possible to replace the $\rho-\omega$ mixing by a direct quark model description. Since the $N-N$ intermediate range attraction described by pion exchange can also be described by quark delocalization and color screening, it is interesting to check whether the pion mass difference effect can be described by a quark effect as well.

Motivated by the reasoning above, we have carried out a quark cluster model calculation of the N-N ^{1}S$_0$ scattering length differences $\Delta a_{CSB} = a_{pp} - a_{nn}$ and $\Delta a_{CIB} = \frac{1}{2}(a_{pp} + a_{nn}) - a_{np}$, where $a_{pp(nn,np)}$ is the $pp(nn, np)$ ^{1}S$_0$ scattering length. The u,d quark mass difference $\Delta m = m_d - m_u$, the q-q electromagnetic interaction V^{γ}_{qq} and the QCD-QED interference induced q-q interaction V^{I}_{qq} are all taken into account in this calculation.

A resonating group method based on the quark cluster model is used to carry out the N-N scattering length calculation[12]. The Hamiltonian of the N-N system is assumed to be

$$
\begin{aligned}
H(1\cdots 6) &= \sum(m_i + \frac{p_i^2}{2m_i}) - T_c + \sum(V^C_{ij} + V^G_{ij} + V^{\gamma}_{ij} + V^I_{ij}), \\
&= \sum(m + \frac{p_i^2}{2m}) - T_c + \sum(V^C_{ij} + \bar{V}^G_{ij}) + \sum(\delta m_i + \delta K_i) + \sum(\delta V^G_{ij} + V^{\gamma}_{ij} + V^I_{ij}), \qquad (1)
\end{aligned}
$$

where m_i is the quark mass, T_c is the total center of mass kinetic energy, the V_{ij} with superscripts C, G, γ and I represent the confinement, gluon exchange, photon exchange and QED-QCD interference q-q interactions respectively; m is the average of the u and d quark masses.

$$
\begin{aligned}
m &= \frac{m_u + m_d}{2} \quad \Delta m = m_d - m_u, \\
\delta m_i &= m_i - m = -\frac{\Delta m}{2}\tau_{iz} \qquad (2)
\end{aligned}
$$

$$\delta K_i = (\frac{1}{2m_i} - \frac{1}{2m})p_i^2 = \frac{p_i^2}{2m}\frac{\Delta m}{2m}\tau_{iz} \qquad (3)$$

$$V^C_{ij} = -a_C \vec{\lambda}_i \cdot \vec{\lambda}_j r^2_{ij} \qquad (4)$$

$$V^G_{ij} + V^{\gamma}_{ij} = (\frac{\alpha_s}{4}\vec{\lambda}_i \cdot \vec{\lambda}_j + \alpha Q_i Q_j)(\frac{1}{r_{ij}} - \frac{\pi}{2}(\frac{1}{m_i^2} + \frac{1}{m_j^2} + \frac{16\vec{S}_i \cdot \vec{S}_j}{3m_i m_j})\delta(\vec{r}_{ij}) + \cdots) \qquad (5)$$

$$\bar{V}_{ij}^{G} = \frac{\alpha_s}{4}\vec{\lambda}_i \cdot \vec{\lambda}_j(\frac{1}{r_{ij}} - \frac{\pi}{m^2}(1 + \frac{8\vec{S}_i \cdot \vec{S}_j}{3})\delta(\vec{r}_{ij}) + \cdots)$$

$$\delta V_{ij}^{G} = V_{ij}^{G} - \bar{V}_{ij}^{G} = -\frac{\alpha_s}{4}\vec{\lambda}_i \cdot \vec{\lambda}_j \frac{\pi}{m^2}(1 + \frac{8\vec{S}_i \cdot \vec{S}_j}{3})\delta(\vec{r}_{ij})\frac{\Delta m}{2m}(\tau_{iz} + \tau_{jz}) \quad (6)$$

$$\begin{aligned} V_{ij}^{I} &= \frac{1}{4}\vec{\lambda}_i \cdot \vec{\lambda}_j(AQ_iQ_jf_{el}(r_{ij}) + BQ_iQ_j\vec{S}_i \cdot \vec{S}_jf_{mag}(r_{ij}) + C(Q_i^2 + Q_j^2)f_{el}(r_{ij}) \\ &\quad + D(Q_i^2 + Q_j^2)\vec{S}_i \cdot \vec{S}_jf_{mag}(r_{ij})) \end{aligned} \quad (7)$$

$$f_{el}(r) = \frac{\frac{1}{r}}{< \frac{1}{r} >_{nucleon}}, \qquad f_{mag}(r) = \frac{\frac{8\pi}{3m^2}\delta(\vec{r})}{< \frac{8\pi}{3m^2}\delta(\vec{r}) >_{nucleon}}$$

Here $\alpha_s(\alpha)$ is the quark-gluon (electromagnetic) coupling constant, a_C is the confinement strength, $Q_i, \vec{S}_i, \tau_{iz}$ and $\vec{\lambda}_i$ are the quark charge, spin, third component of isospin and color SU_3 generators, respectively; A,B,C and D are the parameters[14] of the QED-QCD interference induced quark interactions.

In principle, we can directly use the Hamiltonian (1) and the resonating group method to get both the charge independent and charge dependent N-N interactions[13]. In practice, quark model approaches have not obtained a charge independent N-N interaction as good as the phenomenological or the meson exchange model ones[2, 3]. To focus this study on the charge dependent N-N interaction, we assume the charge independent part can be well described by the Reid soft core phenomenological potential[17]. The resonating group equation for the N-N scattering is thereby reduced to[12]

$$\begin{aligned} &[\nabla^2 + k^2 - \frac{2\mu}{\hbar^2}(V_{NN} + V_{em})]F(\mathbf{r}) = \frac{2\mu}{\hbar^2}\int K(\mathbf{r}, \mathbf{r}')F(\mathbf{r}')d\mathbf{r}' \\ &K(\mathbf{r}, \mathbf{r}') = -9\langle[\psi_{N_1}(1,2,3)\psi_{N_2}(4,5,6)]_{ST} \mid \sum_{\alpha} O_{\alpha} \mid P_{34}[\psi_{N_1}(1,2,3)\psi_{N_2}(4,5,6)]_{ST}\rangle \end{aligned} \quad (8)$$

where the V_{NN} is the Reid soft core potential, V_{em} is the direct electromagnetic interaction between nucleons, μ is the reduced mass $\mu = \frac{M_n+M_p}{4}$, ψ_N is the quark model nucleon wave function (color singlet, $SU_4^{\sigma\tau}$ symmetric, Gaussian orbital with a size parameter b), P_{34} is a quark exchange operator, $[\ ]_{ST}$ means the nucleon spin-isospin is coupled to the channel spin S and isospin T. The O_{α} are the five charge dependent terms: $\delta m_i, \delta K_i, \delta V_{ij}^{G}, V_{ij}^{\gamma}$ and V_{ij}^{I}. The first four terms have been studied in [12]. Here we concentrate on the effects of the last term, the QED-QCD interference, V_{ij}^{I}.

We take two approaches to study the effect of V_{ij}^{I}. One is to follow GMS[14], i.e., assume that the QED-QCD interference induces a q-q interaction as shown in Eq.(7), and fix all model parameters (the average u, d quark mass m, the u, d quark mass difference Δm, quark gluon coupling constant α_s, nucleon size b and parameters A, B, C, D) from an overall fit to baryon isomultiplet mass splittings. We call this a phenomenological model (MP). Due to the relatively large errors involved in the experimental hadron masses used in the overall fitting, especially those of Σ^* and Σ_c, GMS tested 135 sets of parameters. The results listed in Table I, labeled by MP,

correspond to their most favorable set. Other parameter sets have been tested as well, but not $\Delta m < 0$ cases, because those are unacceptable from the general point of view on the quark mass difference [4]. In Table I, two additional results, labeled as MP I and MP II, are listed to indicate the level of sensitivity of the N-N scattering lengths to the variation of the phenomenological parameters. The other approach is to take the A, B, C and D parameters from a perturbative QED-QCD calculation [18], which includes the vertex electromagnetic penguin, photon and gluon box and crossed box diagrams. The interference interaction calculated this way is

$$V_{ij}^{I} = \frac{1}{4}\vec{\lambda}_i \cdot \vec{\lambda}_j \alpha_s \alpha \{ \frac{16(1-\ln 2)}{4\pi} Q_i Q_j \frac{1}{r_{ij}} - \frac{12(1+\ln 2)}{m^2} Q_i Q_j \vec{S}_i \cdot \vec{S}_j \delta(\vec{r}_{ij}) - \frac{4}{3}(Q_i^2 + Q_j^2)\frac{\vec{S}_i \cdot \vec{S}_j}{m^2}\delta(\vec{r}_{ij}) + \cdots \} \tag{9}$$

There are many other terms in the perturbative QED-QCD interference calculation result beyond those explicitly shown here. Only the three terms shown in Eq.(9), which have the same form as assumed by GMS[14], have been included in our scattering calculation. As the QED-QCD interference effect is nonperturbative, we should perform a nonperturbative calculation. However from the phenomenological success of the effective one gluon exchange Breit-Fermi interaction, we expect that a perturbative calculation of the QED-QCD interference interaction is useful in the study of the GMS effect, because we are doing a QED correction to the effective one gluon exchange. We call this a QCD model (MQ). The parameters other than those that appear in Eq.(9) are determined by re-fitting the n-p and Δ mass differences with two choices of the nucleon size b but fixed α_s. They are labeled as MQ I and MQ II in Table I.

Altogether there are five model results listed in Table I. The corresponding five parameter sets are listed together in Table II. In order to show the effect of the individual QED-QCD interference terms, in the first to fourth rows of Table I, we list the scattering length corrections, $\Delta a_{ij} = a_{ij} - a_{NN}$, due to each of the A, B, C and D terms in Eq.(7). The charge independent Reid soft core potential V_{NN} in Eq.(8) is always included; it gives a charge independent $a_{NN} = -17.13$ fm. The different terms increase or decrease the scattering lengths differently. The fifth row is the correction due to the coherent sum (A+B+C+D) of the four terms in Eq.(7). The sixth row lists the scattering length corrections due to the coherent sum of all other relevant effects: the quark mass difference, gluon and photon exchange interactions, i.e., $\delta m + \delta K + \delta V^G + V^\gamma$. The last row, labelled Full, lists the overall results with the five charge dependent terms of Eq.(1) all included.

It should be noted that the total scattering length correction is not always equal to the sum of the individual ones, even though the individual corrections to the scattering length are small.

The main feature we find is that the corrections due to different charge asymmetry interactions tend to cancel each other and affect the scattering length coherently.

Because we based our calculation on the Reid soft core which gives a charge independent $a_{NN} = -17.13$ fm, quite close to the nuclear p-p scattering length, the only meaningful quantities from our analysis are the charge symmetry breaking scattering length difference $\Delta a_{CSB} = a_{pp} - a_{nn}$ and the charge independence breaking scattering length difference $\Delta a_{CIB} = \frac{1}{2}(a_{pp} + a_{nn}) - a_{np}$ (expressed as Δa_{CD} in [4]). Our model results Δa_{CSB} and Δa_{CIB} are listed in Table II together with the corresponding model parameters.

For the GMS phenomenological models, the calculated Δa_{CSB}($\sim$2-3 fm) is too large in comparison with the value of 1.5 fm recommended in Ref. [4]. The Δa_{CIB} ($\sim$1 fm) is much too small in comparison with 5.7 fm recommended in Ref. [4] and for the GMS most favorable parameter set it is -1.5 fm, which is the wrong sign. These results are consistent with those of [19].

Interestingly, and perhaps even surprisingly in view of their perturbative origins, the QCD models produce better results. The MQ II leads to Δa_{CSB}=2.16 fm, Δa_{CIB}=7.33 fm, which are not too different from the recommended values of 1.5 and 5.7 fm respectively. As a further demonstration of the plausibility of the QCD models, in Tables I and II we added an additional result, labelled as MQP, where the parameters are constrained by the n-p and $\Delta^{++}-\Delta^0$ mass differences. It gives Δa_{CSB}=1.50 fm and Δa_{CIB}=5.73 fm, almost identical to the values recommended in [4].

We conclude that, taking into account the quark mass difference, the electromagnetic interaction and the QED-QCD interference effects together, it is possible, using a quark cluster model, to deduce the charge dependent effects found in the N-N interaction. However, with the present model parameters, the GMS phenomenological model can not explain the charge asymmetry appearing in the N-N $^1S_0$ scattering lengths. The perturbative QCD model appears plausible, but further quantitative work is needed.

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Note added. After this work was completed, we learned of Ref.[20], which independently finds that heavy baryon mass splittings cannot be consistently described without the inclusion of the interference terms studied here (which they refer to as "electromagnetic penguins"), despite consideration of several other different possible additional contributions besides the conventional ones of quark mass and photon exchange effects. The need for "electromagnetic penguins" in heavy-light systems has also been argued in Ref.[21].

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Table 1. N-N $^1S_0$ scattering length corrections.

		MP	MPI	MPII	MQI	MQII	MQP
A	Δa_{pp}	0.05	0.04	0.04	-0.03	-0.09	-0.09
	Δa_{nn}	0.01	0.01	0.01	-0.00	-0.01	-0.00
	Δa_{np}	1.58	1.24	1.08	-1.32	-2.65	-3.82
B	Δa_{pp}	-2.45	-2.28	-1.96	1.54	1.60	0.67
	Δa_{nn}	-1.12	-1.05	-0.91	0.79	0.79	0.34
	Δa_{np}	-0.38	-0.36	-0.31	0.29	0.31	0.13
C	Δa_{pp}	-1.88	-0.5	0.30			-1.01
	Δa_{nn}	-1.53	-0.42	0.25			-0.83
	Δa_{np}	-1.70	-0.46	0.28			-0.92
D	Δa_{pp}	2.90	-0.16	-3.18	0.17	0.20	0.98
	Δa_{nn}	1.07	-0.05	-0.93	0.06	0.08	0.33
	Δa_{np}	2.04	-0.11	-1.99	0.11	0.14	0.66
A+B+C+D	Δa_{pp}	-0.33	-3.11	-5.40	1.65	1.69	0.67
	Δa_{nn}	-1.42	-1.58	-1.64	0.84	0.85	-0.12
	Δa_{np}	1.88	0.41	-0.70	-0.87	-2.07	-3.91
$\delta m + \delta K + \delta V^G + V^\gamma$	Δa_{pp}	1.17	1.90	2.37	2.04	1.81	1.17
	Δa_{nn}	0.20	-0.71	-1.39	-0.90	-0.19	0.2
	Δa_{np}	-0.66	-0.66	-0.66	-0.66	-0.81	-0.66
Full	Δa_{pp}	0.87	0.99	1.51	3.20	2.73	1.75
	Δa_{nn}	-1.19	-1.22	-1.94	-0.16	0.56	0.08
	Δa_{np}	1.36	-1.23	-1.23	-2.64	-5.69	-4.89

Table 2. Calculated $\Delta a_{CSB}, a_{CIB}$ and the model parameters.

	m(MeV)	Δ m(MeV)	α_s	b(fm)	A(MeV)	B(MeV)	C(MeV)	D(MeV)	Δa_{CSB}	Δa_{CIB}
exp.									~ 1.5	~ 5.7
MP	330	0.6609	1.624	0.617	-1.666	5.894	5.340	-6.258	2.06	-1.52
MPI	330	3.7724	1.624	0.617	-1.278	5.543	1.551	0.296	2.21	1.12
MPII	330	5.8927	1.624	0.617	-1.104	4.844	-0.953	4.861	3.45	1.02
MQI	330	4.37	1.624	0.617	1.182	-4.592	0	-0.301	3.36	4.26
MQII	330	1.91	1.624	0.80	0.911	-2.032	0	-0.133	2.16	7.33
MQP	330	0.6609	1.624	0.617	2.804	-2.444	2.824	-1.040	1.50	5.73